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Road and Structure Protection Through Weight Control

Economic and Engineering Issues

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Economic and Engineering Issues

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1/ INTRODUCTION

The primary purpose of any highway system is to permit safe and economical movement of goods and people about the country. The quality of the highway system greatly influences the effectiveness and costs of road transportation and, certainly, plays a significant role in the economic and social development of various regions in a country. Recognizing this, progressive countries have, in past years, spent vast sums of money to improve and upgrade their road systems to accept modern road transport vehicles. Many truck transport vehicle owners will continually strive to reduce their unit tonne-kilometre cost by loading vehicles to capacity, either by volume or weight. Some fully loaded vehicles carrying high-density products, such as minerals, will have much higher axle and gross loads than fully loaded trucks carrying mixed goods. These heavily loaded vehicles can create significant pavement damage, resulting in traffic delays for maintenance purposes, and, sometimes, can even trigger collapse of older bridges, resulting in closures of the route. Many fully loaded vehicles can exceed safety margins of components of their vehicles, and this can cause accidents due to loss of control. Avoiding excessive pavement and bridge damage, which degrade the value of the highway system, and reducing risks due to unsafe loading practices are the principal reasons for vehicle weight laws.

Traditionally, vehicle weight laws have been based on limiting axle loads and gross loads (in the U.S.A., currently to 20 000 lb (9 tonnes[t]) and 80 000 lb (36 t), respectively. It is recognized that for pavements the important factor is the axle load and that gross loads of large magnitudes can be accommodated by pavements, given that there is an adequate number of wheels to distribute the load. For bridge structures, it is recognized that axle load, axle spacing, and gross load are all important factors, even though gross load becomes more important as the bridge span becomes large.

In 1971, recognizing that the upper limits of safe truck loads were controlled by the load capacity of bridges, Ontario changed its weight laws to one controlled by a bridge formula, but retained axle weight limitations to safeguard pavements. Ontario's weight laws now allow

permissible gross vehicle loads of 63.5 t, among the highest permissible loads anywhere in the world.

1.1/ Economic Factors

The total cost of moving goods by truck over a highway system breaks into two basic components. First, there are the public costs associated with construction and maintenance of the road network. Second, there are the privately financed costs of acquiring, operating, and maintaining the fleet of trucks operating over the road system. These publicly and privately financed costs are directly linked in many ways. For instance, the more trucks there are, the more wear and tear to the highways; the greater the loads permitted on each axle, the higher are road construction and maintenance costs; the worse the condition of the highway system, the greater are vehicle operating costs.

To ensure that these two components of the transportation system, the vehicles and the roads, are compatible with each other and to attempt to keep the overall private and public expenditures on the total system to a minimum, it is necessary to establish design and maintenance standards for the roads and limits on the weights and dimensions of trucks. The maximum length, height, and width of vehicles on the system influence the geometric design standards for the highways, whereas weight limits control the design of the pavement strength and of structures.

There is considerable economic advantage to truckers to have higher permissible gross weights. As trucks increase in size, operating costs per kilometre increase, but the cost per tonne-kilometre of goods moved generally decreases. However, as axle loading increases, pavement damage increases rapidly, and therefore, construction and maintenance costs increase. Since funding for highway construction and maintenance is usually constrained, it is necessary to set axle weight limits which do not result in requirements for highway funding in excess of the funds available. A balance has to be achieved between the limits that truckers may desire and the resultant highway costs that can be afforded. Ideally, this balance should result in the minimum overall cost.

Once weight limits are established, it is essential that these weight controls be enforced. Without enforcement, truckers will tend to overload their trucks, whether it is to their economic advantage or not. Therefore, an effective enforcement program is required. The cost of this enforcement program is a third factor in the overall cost of the total transportation system. However, this tends to be small in comparison to the others.

Finally, since pavement damage increases rapidly with increasing axle loading, heavy trucks tend to cause the most pavement damage. Therefore, heavy trucks should bear more of the cost of providing the highway system than other users. The paper touches briefly on the "user-pay" concept.

2/ VEHICLE OPERATING COSTS

While it is generally accepted that as truck weights increase, there are savings in transportation costs, it is difficult to obtain reliable statistics. There are many reasons for this. Many trucking companies simply do not have a large enough range of vehicle sizes in their fleets. They tend to specialize in either long distance, heavy trucking or in local cartage and delivery, using smaller vehicles. Since the operating practices of different companies are quite different, it is difficult to make comparisons. Furthermore, many trucking companies are quite reluctant to disclose their costs, not wishing such information to fall into the hands of their competitors. Still others do not keep records which can be readily traced back to individual trucks.

However, for the purpose of this paper, 1984 representative figures were obtained from the Ontario trucking industry. Costs included in the analysis are broken down by power units and trailers and include maintenance costs, tires, licences, fuel, wages, and capital costs. In assessing the capital cost, the initial cost was amortized over the average life of the vehicle, and the recovery value of the unit was also spread over the life of the vehicle as a annual credit. This net annual cost was then prorated as a cost per kilometre, assuming about 160 000 km per year per truck. An interest rate of 8% was used for the calculations, being an approximation of the real value of money (prime rate less inflation rate). Although the selection of an appropriate rate of interest is

always arguable, the overall results are not particularly sensitive to the interest rate selected.

Capital costs account for up to 20% of the total costs per kilometre. The useful life of straight trucks and tractors was assumed to be seven and six years, respectively, while that of trailers was assumed to be 10 years. The resale values used assume all equipment to be in average to good condition at time of sale. The operating costs are for a complete vehicle (e.g., tractor and trailer), whereas the capital costs are for each unit. Most carriers have more trailers than tractors. A ratio of 2.5:1 was considered representative of the industry in Ontario, and the annual capital costs for trailers were adjusted accordingly.

Eight truck sizes are included in the analysis, as follows:

	Gross Weight (tonne)
1/ Cube Van -- single drive axle	4.54
2/ Straight truck -- single drive axle	12.47
3/ Single drive axle tractor -- single axle trailer	22.68
4/ Single drive axle tractor -- single axle trailer	25.40
5/ Single drive axle tractor -- tandem axle trailer	32.66
6/ Tandem drive axle tractor -- tandem axle trailer	38.56
7/ Tandem drive axle tractor -- tri-axle trailer	49.90
8/ Tandem axle trailer -- two single axle trailers and one single axle dolly	52.62

The various cost components for these trucks are shown in Table 1.

2.1/ Capital

As a percentage of the overall cost per kilometre, capital costs rise steadily from about 6% for the smallest trucks, levelling off at about 20% for the largest trucks.

2.2/ Maintenance

Maintenance costs increase slowly over the full range of trucks, varying between 14 and 23% of the overall cost per kilometre.

Table 1/ Vehicle Operating Costs

TRUCK NO	1	2	3	4	5	6	7	8
Gross Weight (Tonne)	4.54	12.47	22.68	25.40	32.66	38.56	49.90	52.62
Max Payload (Tonne)	2.49	6.58	9.57	12.02	18.01	22.68	32.30	38.43
CAPITAL COSTS $								
Power unit cost	20,000	35,000	40,000	46,000	48,000	58,000	61,500	61,500
Trailer cost	-	-	17,500	17,500	23,000	23,000	29,000	41,500
Power unit resale value	4,480	7,840	11,600	13,340	13,920	16,820	17,835	17,835
Trailer resale value	-	-	2,310	2,310	3,036	3,036	3,828	5,478
Power unit cost/yr.	3,339	5,844	7,071	8,132	8,486	10,254	10,872	10,872
Trailer Cost/yr.	-	-	6,121	6,121	8,045	8,045	10,144	14,516
COST/KM $								
Capital	.021	.036	.082	.089	.103	.114	.131	.158
Power maintenance	.056	.056	.061	.062	.075	.087	.099	.112
Trailer maintenance	-	-	.022	.024	.031	.035	.043	.070
Power Tires	.007	.009	.010	.011	.011	.017	.017	.019
Trailer Tires	-	-	.003	.003	.005	.005	.008	.009
Fuel	.083	.113	.142	.146	.155	.172	.193	.205
Licences	.001	.003	.006	.008	.010	.011	.015	.016
Wages	.184	.184	.184	.184	.184	.185	.185	.185
TOTAL $/km	.352	.401	.510	.527	.574	.626	.691	.774
¢/Tonne km	14.14	6.09	5.33	4.38	3.19	2.76	2.14	2.32

2.3/ Tires

The cost of tires for all truck sizes is a small proportion of the overall costs, varying between 2 and 4%.

2.4/ Fuel

Fuel costs are a significant factor, but are surprisingly uniform as a percentage of the total cost per kilometre. For all sizes of trucks, fuel accounted for 24 to 30% of the total costs.

2.5/ Wages

Since the cost of wages is virtually constant for all truck sizes, it accounts for a very high proportion of the smallest trucks' costs (over 50%), declining steadily to less than 25% for the largest trucks.

2.6/ Licences

In Ontario, the cost of licensing is a relatively insignificant factor as a proportion of the overall costs, generally less than 2%.

Figure 1 illustrates these various cost components graphically. It can be seen that, for all components, cost increases are reasonably linear as gross vehicle weight increases. Figure 2 shows the same data, with the costs of each component expressed as a percentage of the overall cost. This graph shows more clearly that fuel, maintenance, and capital costs become steadily more significant with increasing truck size but that the importance of wages drops very quickly.

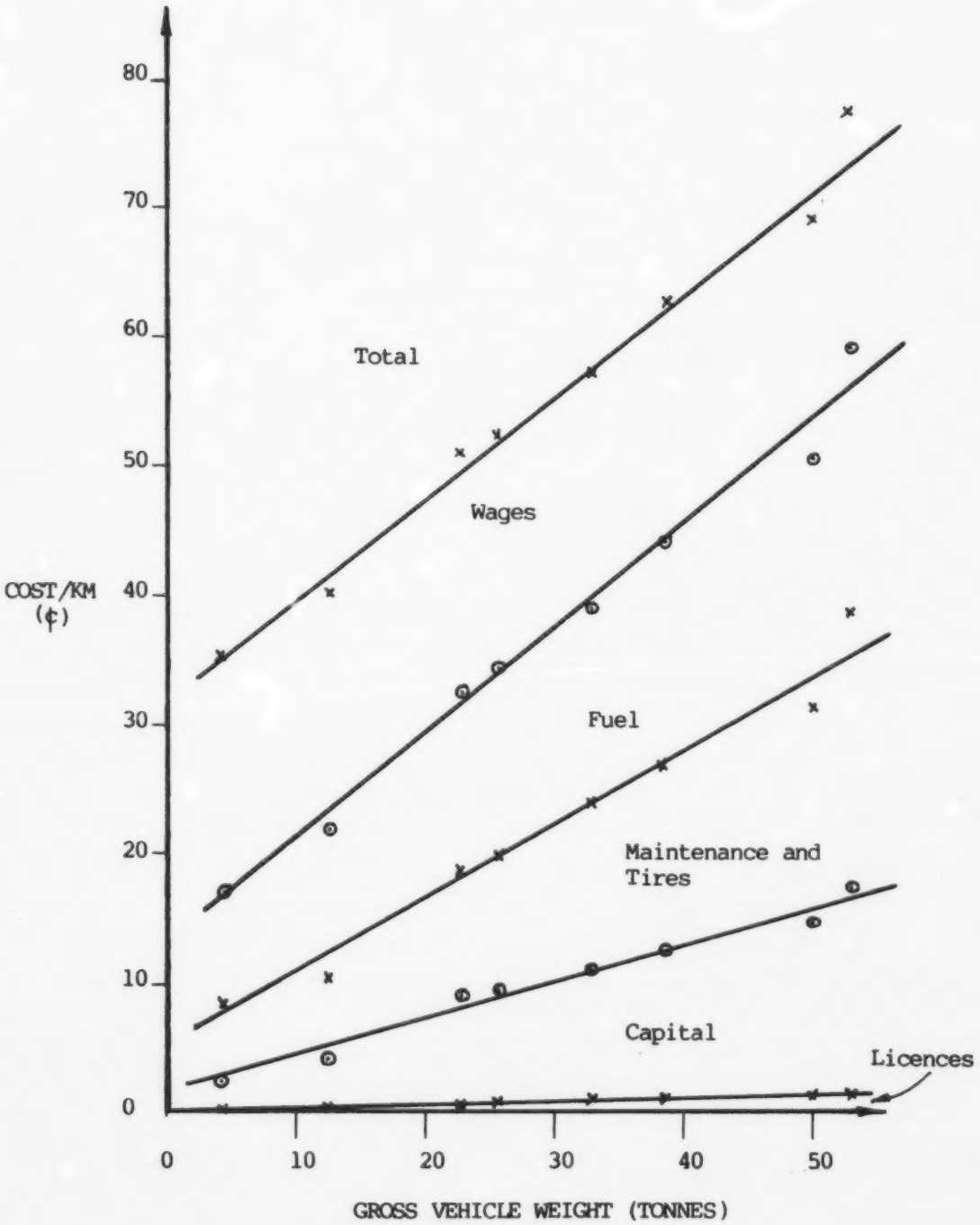

Figure 1/ Variation in Operating Cost/km

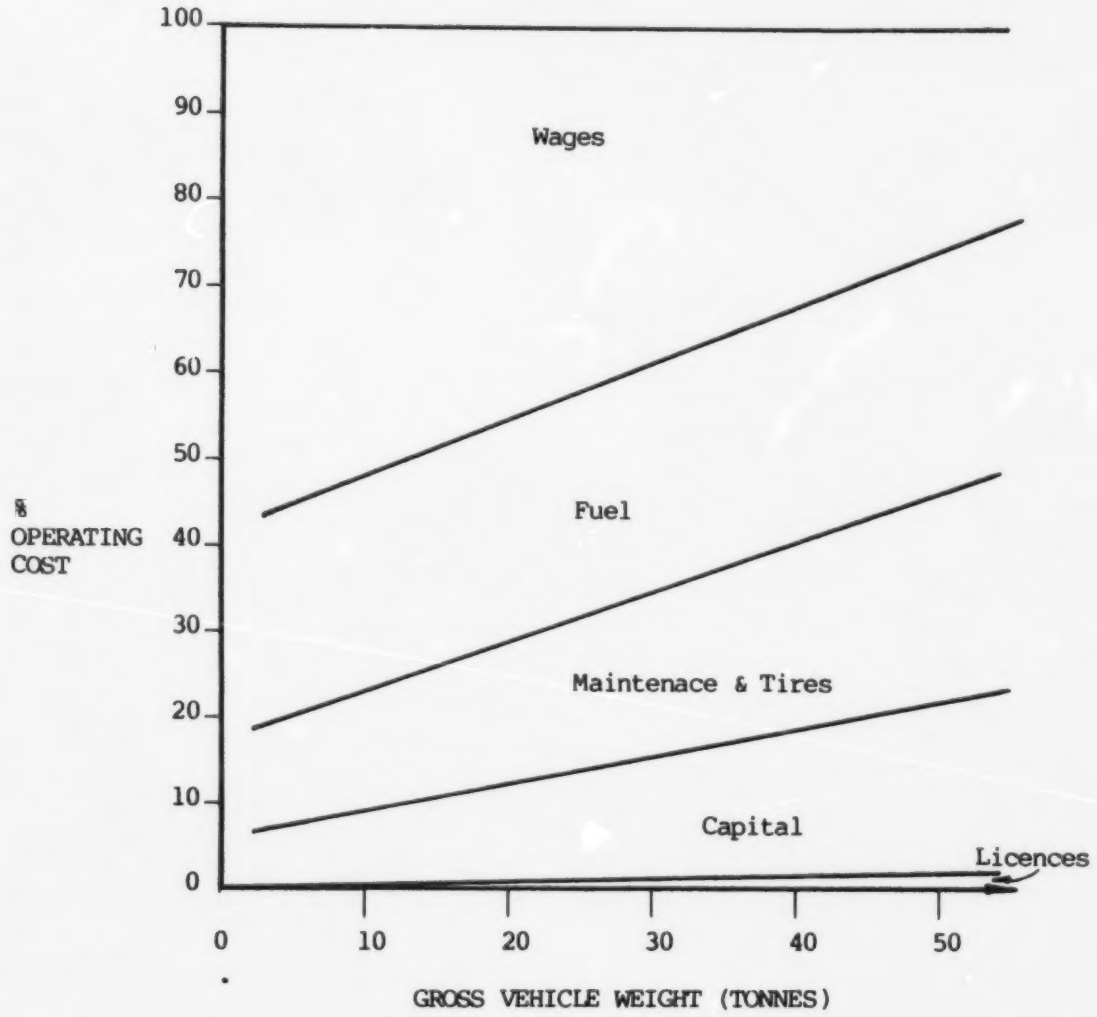

Figure 2/ Percentage Cost Breakdown

Figure 3 shows the total costs expressed as cost per tonne-kilometre of goods carried. It can be seen that, initially, costs per tonne-kilometre drop dramatically as the truck size increases. However, above 40 to 50 t gross weight, cost improvements are marginal. At each change in basic vehicle type, there is a distinct discontinuity in the curve. It is apparent that in the absence of axle load restrictions, there would be a financial advantage to the vehicle operators in carrying heavier loads on single unit vehicles rather than tractor trailers. This is no doubt the reason for a large number of very heavy single unit trucks in some countries. Since the price of fuel varies worldwide and can represent a significant proportion of operating costs, the total cost of operation less fuel costs is also shown in Figure 3. As can be seen, this merely moves the curves down without significantly changing their shape. It is apparent that the cost of fuel has little or no effect on the point at which further increases in truck size result in little or no further cost savings.

It is difficult to compare these operating costs directly with results obtained in other studies for a number of reasons. First, operating conditions range considerably from one country to another, due to such factors as climate, road conditions, terrain, etc. Also, different assumptions are made regarding the various cost components and about the vehicle load condition. A further problem is that the costs of various components vary differently over time and may, in any case, be quite different in different countries. Furthermore, these costs are very quickly dated. Nevertheless, despite the cumulative effects of these different conditions and assumptions, the general shape of the curves produced by various studies is very consistent. Figure 4 shows a selection of results from other studies. The curve for this study was obtained by tracing a curve around the lowest portions of the three curves for different vehicle types. This approach has been used by other studies and represents the optimum vehicle from the operators point of view. The cost scales for the various studies were adjusted to achieve a good fit between the various curves. This approach is acceptable since

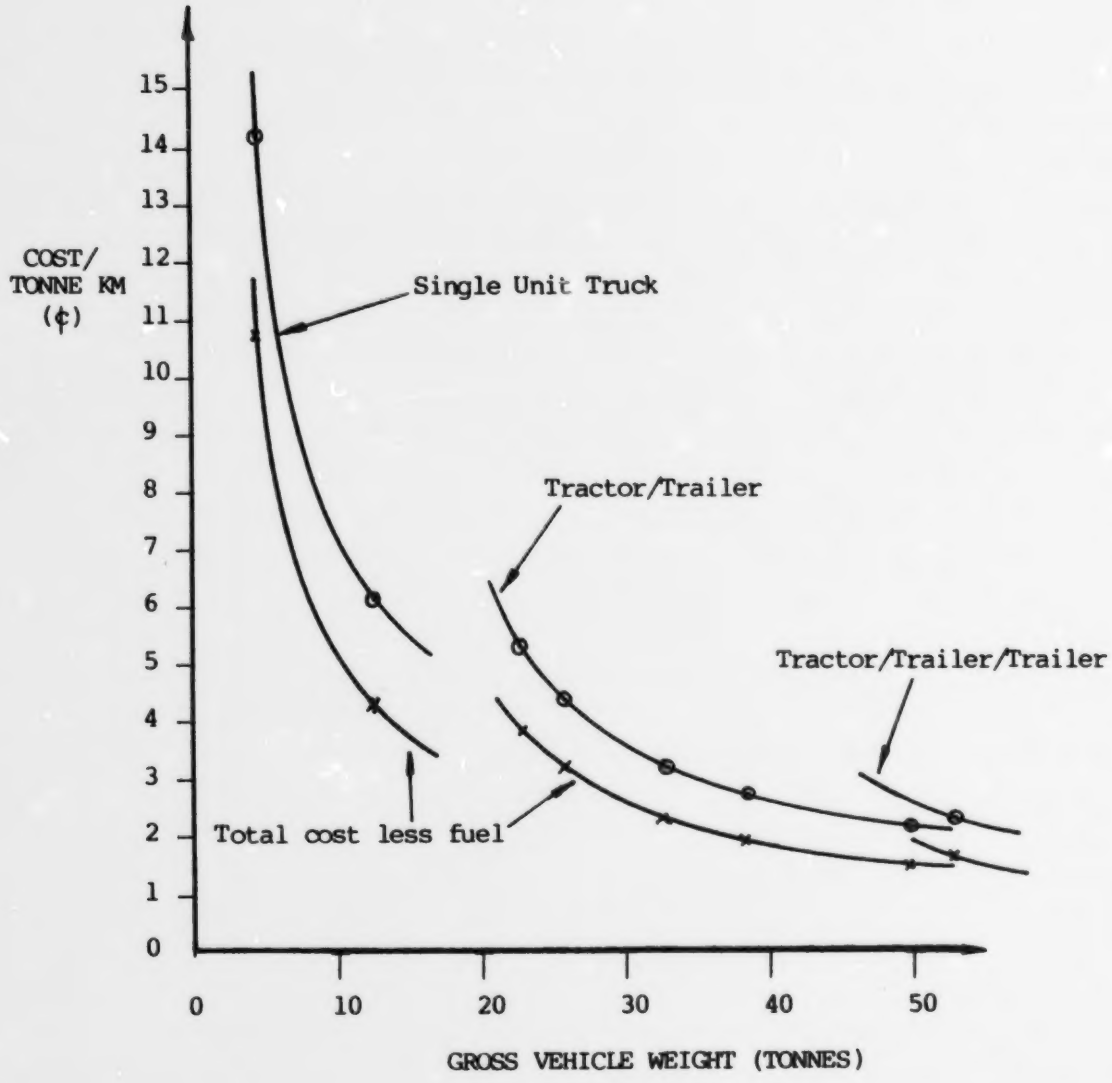

Figure 3/ Vehicle Costs/Tonne-km

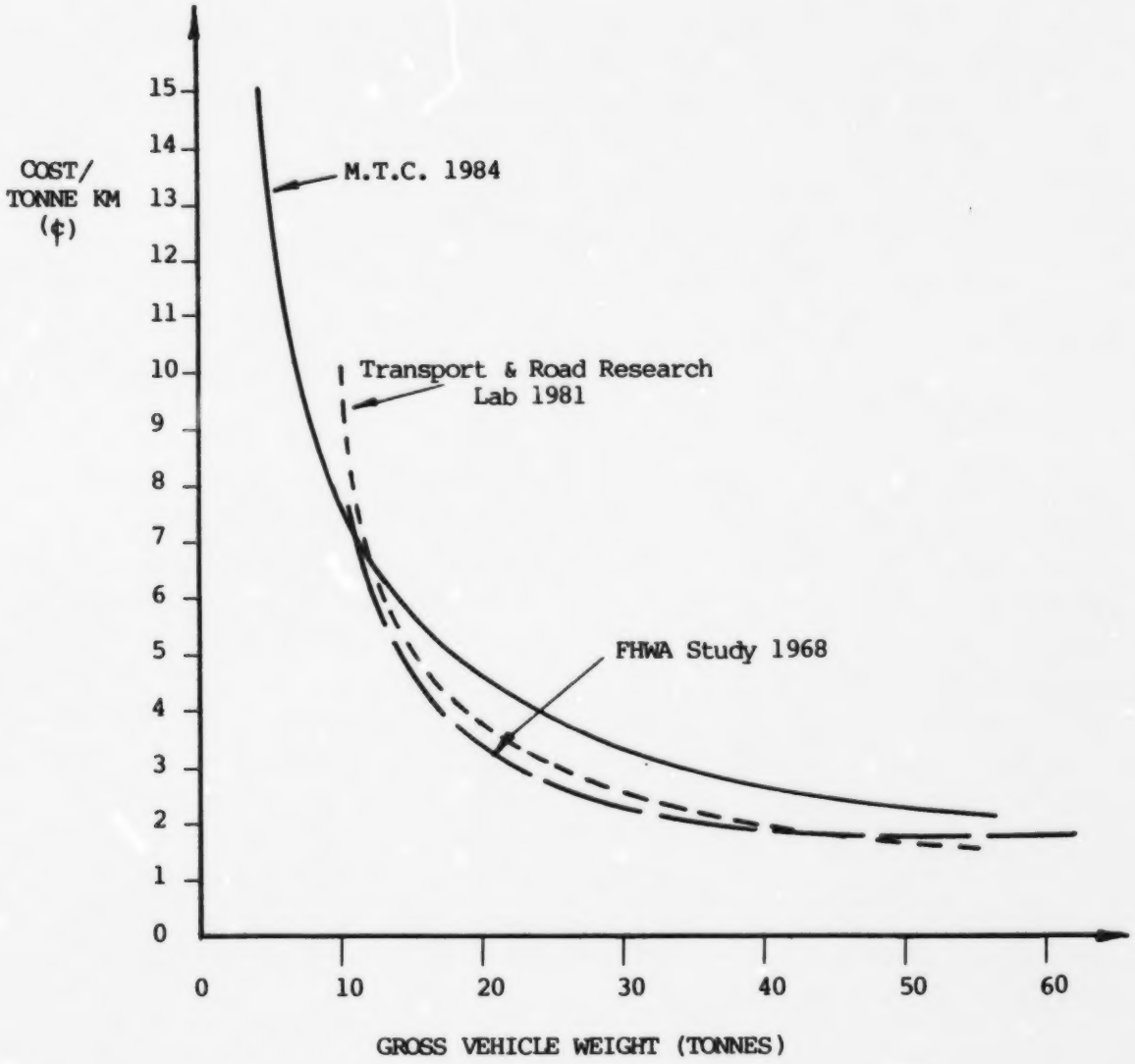

Figure 4/ Comparisons of Vehicle Operating Costs

the significant feature of these curves is the point or range at which there is little or no further cost decrease with increasing gross weight. All of these curves appear close to this point, in the range of 40 to 60 t. Therefore, above this range there is very little or no further economic benefit to the vehicle operator. Ontario allows gross vehicle weights of 63.5 t. At such a level, costs per tonne-kilometre may actually be starting to increase, as has been demonstrated by some authors.

3/ ROAD CONSTRUCTION AND MAINTENANCE COSTS

3.1/ Pavements

Pavement structures are made up of layers of increasingly stable materials placed on the natural ground. The function of the pavement structure is to spread the imposed loads so that the stresses imposed on the natural ground do not cause fracture or permanent deformation. The pavement surface itself is subjected to large and complex stresses as vehicles start up, brake, or make sharp turns. This requires a material which possesses some tensile strength, such as bituminous pavement or concrete. Stresses in lower layers reduce sharply with depth, so that unbound granular materials are quite acceptable. The thicknesses of the layers, strength, and deformation characteristics of the paving materials used, and the condition and characteristics of the natural subgrade soil, control the load capacity of the pavement structure. Drainage of water, which can substantially weaken the pavement structure, is an important consideration in pavement design and maintenance.

The relationship between pavement damage and axle load is generally accepted to be of the form:

$$\text{Damage} = k \times (\text{axle load})^4$$

This fourth power relationship is based on the AASHO Road Test. However, under some conditions, the value of the exponent can vary significantly. In theory, using this equation, the total damage to a pavement over the design life of the road could be calculated by summing the damage caused

by each axle passing over the road during its life. This, to say the least, would be a tedious calculation. In practice, traffic volumes and the proportion of truck traffic are used to derive the number of "equivalent axle loads" imposed over the life of the road, thus calculating the total damage. The effect of the fourth power relationship is dramatic. If axle loads are not controlled and the average truck axle loading increases from say 8 to 10 t, then assuming the same number of trucks, pavement damage could increase by almost 150%. This illustrates the importance of a weight control program. However, in practice, damage would probably be somewhat less than this, for if axle weights rose, presumably the total number of trucks would decrease, which would offset some of the increase in damage.

Fortunately, significant increases in pavement strength can be achieved with reasonable modest increases in the cost of the pavement. For instance, if the pavement depth were increased at an additional cost of 15%, then the strength of the pavement could increase by about 200% or more. Therefore, if it is desirable to increase permissible axle loads to permit larger trucks to use the system, pavement strengthening can be achieved by adding an overlay of 30 to 50 mm of new pavement material. However, if such strengthening were required over most of the road network, then the total expenditures would be very significant.

From the preceding, it is apparent that for a given increase in permissible axle weight loadings, it is possible to calculate the cost of the required pavement strengthening and the resulting cost benefits to the trucking community. In allocating this additional funding to the road system, it is not necessary to strengthen all roads immediately. All roads deteriorate over time. As shown in Figure 5, once the pavement condition rating reaches a certain level it requires resurfacing. However, if resurfacing is unduly delayed, complete reconstruction will be required. This is far more costly. When permissible axle weight levels are increased, the rate of deterioration of the pavement will increase, as shown in Figure 6. Therefore, those pavements with higher deterioration over time and those already near the point where resurfacing is required should be resurfaced first. For other roads, the timing of resurfacing may have to be advanced but need not be done immediately. However, if resurfacing is delayed too long, reconstruction will now be required earlier at much higher costs.

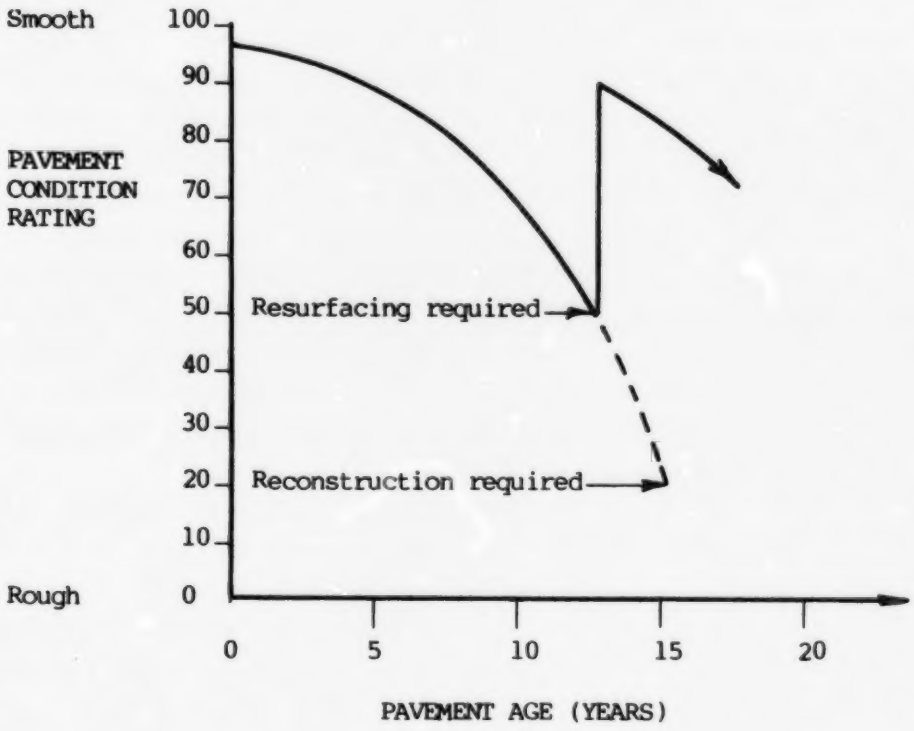

Figure 5/ Pavement Deterioration

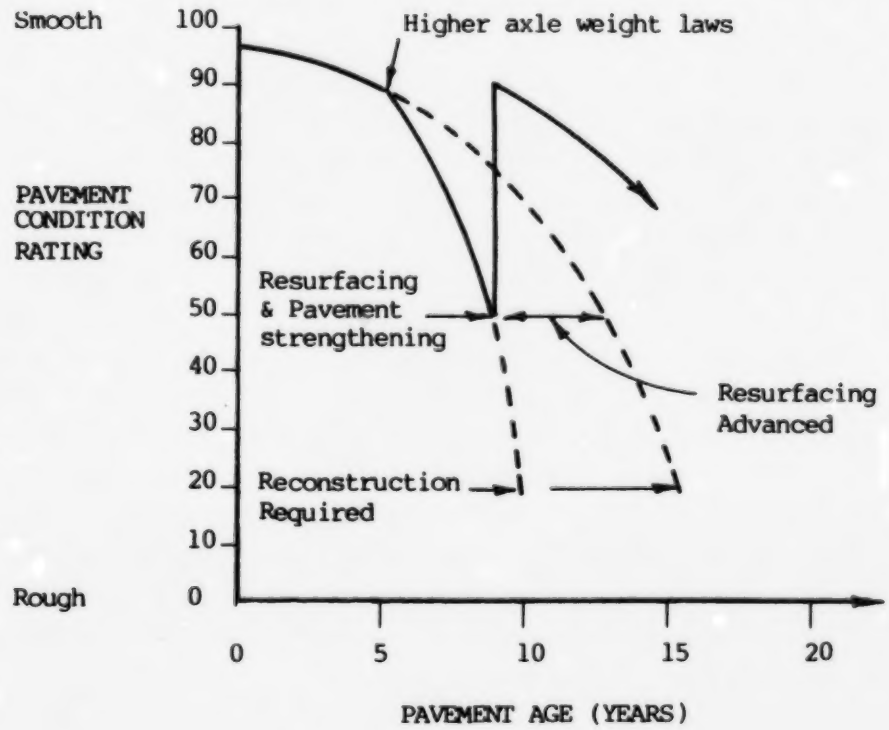

Figure 6/ New Axle Weight Limits Introduced

3.2/ Structures

Bridge structures are designed to support a specific load, such as the ASSHTO HS20 truck. This design vehicle has axle loads of 8000 lb (3.6 t), 32 000 lb (14.5 t), and 32 000 lb (14.5 t) spaced at 14 ft (4.3 m) and 14 ft (4.3 m) to 30 ft (9 m) apart, for a gross load of 72 000 lb (33 t). However, bridges can support larger loads, provided they are distributed over a longer length in such a way as not to increase the stresses over and above what is produced by the HS20 design load. Nevertheless, the load capacity of the bridge is often stated as being the 72 000 lb (33 t) design load. The HS20 truck was used for the design of bridges in Ontario until the Ontario Highway Bridge Design Code (OHBDC) was introduced in 1979.

In the late 1960s there was pressure from the trucking industry in Ontario to increase the legally permitted weights of vehicles. It was important to determine what changes could be allowed, from the viewpoint of bridge performance. An investigation of existing bridges showed that loads well in excess of original design loads could be permitted, at a satisfactory safety level, using new analytical and load-testing techniques. As a result, the legal gross vehicle weights were increased substantially in 1971, with a maximum weight of 140 000 lb (63.5 t).

The existing truck population was first surveyed, and the new legal loads were defined, with the effect of truck loads on bridge behaviour being the key determinant. To assess the effect of thousands of different trucks on various bridge types, the equivalent base length concept was developed. The equivalent base length B_m is defined as a length over which the total weight of a group of axles can be uniformly distributed to cause load effects in a bridge structure similar to those caused by the group of axles itself. By plotting weight against B_m for all trucks and axle sub-configurations, a curve close to an upper bound curve was selected as the legal load curve. The equation of the selected curve, known as the Ontario Bridge Formula (OBF), was

$$W_m = 20 + 2.07\ B_m - 0.0071\ B_m^2$$

where W_m = permissible weight in kips and B_m is in ft, as shown in Figure 7.

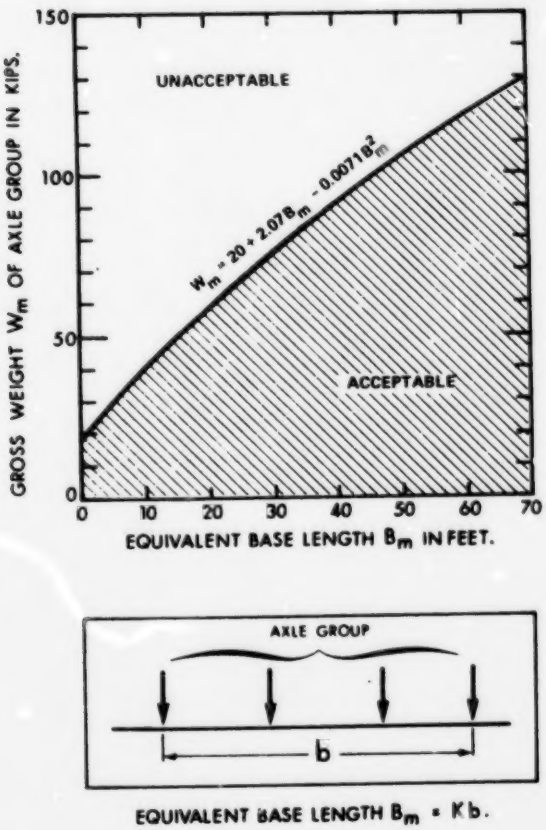

Figure 7/ Ontario Bridge Formula

The OBF in metric units is

$$W_m = 9.806\ (10.0 + 3.0\ B_m - 0.0325\ B_M^2)$$

where W = permissible weight in kN and

B_m is in m.

Although the Ontario Bridge Formula may appear simple, it was not easy for truck drivers or magistrates to understand, and overload charges were rarely successful in court until the formula was replaced by a series of weight tables.

The increased permissible weights have had a large economic payoff for the trucking industry, without any apparent acceleration in load-induced bridge and pavement deterioration.

In 1976 the Ministry embarked on the development of the Ontario Highway Bridge Design Code, which defined the design live load for bridges to reflect actual truck loads. A more consistent bridge safety level was established by calibrating bridges, using a limit states design format. This new code has enabled higher loads to be safely carried at no increase in material compared to the previously used AASHTO Specifications.

Ongoing vehicle weight surveys and vehicle weight studies led to the definition of the new loading model for design and evaluation in the code. The bridge design loads, posting loads, and overweight permit loads are now all related directly to the legal OBF loads. The effects on bridges and pavements of any proposed increase in legal loads can thus be more systematically evaluated. This consistent approach to legal load levels, overload permits, design loads, and evaluation loads, all based on the equivalent base length concept, has enabled the Ministry to maintain the legal load levels established in 1971, virtually unchanged for the last 13 years. During this time, the legal loads have been the highest of any jurisdiction in North America, without a higher incidence of load-related problems on bridges being apparent.

3.3/ Weight Control Enforcement

Weight controls are of no value unless they are enforced. Without enforcement, operators will tend to overload their trucks to try to save cost. Weight enforcement requires not only the physical means to determine whether a vehicle is exceeding the legal load, but also a visible presence to let people know that the law will be enforced.

In Ontario, vehicle sizes and weights have continued to grow over the years, even with enforcement, as shown in Figure 8. Without enforcement, the growth in size and weight could be at such a rapid pace that the acceleration in damage to pavements and bridge structures would severely tax the capability to maintain them.

If size and weights of axles and vehicles are not controlled, the risk of catastrophic bridge failures will rise markedly. This may even threaten the integrity of the entire highway network if weights greatly exceed design loads and use up the built-in safety factors.

One could design bridges to carry heavier loads certainly, but it would require large amounts of money and a time span of many decades to replace existing bridges designed for lower load capacities. So it can be said that weight enforcement is an essential ingredient of highway maintenance.

In order for weight laws to be easily enforced, they must be kept as simple as possible so that operators know when they are in compliance and inspection staff can easily determine when they are not.

Obviously, effective enforcement requires both staffing and a system of weigh scales. However, the cost of enforcement is relatively small in comparison to other expenditures on the highway system. In Ontario, the annual cost of enforcement is estimated at less than $7 million, whereas the annual cost of maintenance and rehabilitation work is over $140 million. Without weight enforcement, this figure could easily jump by 20 or 30%.

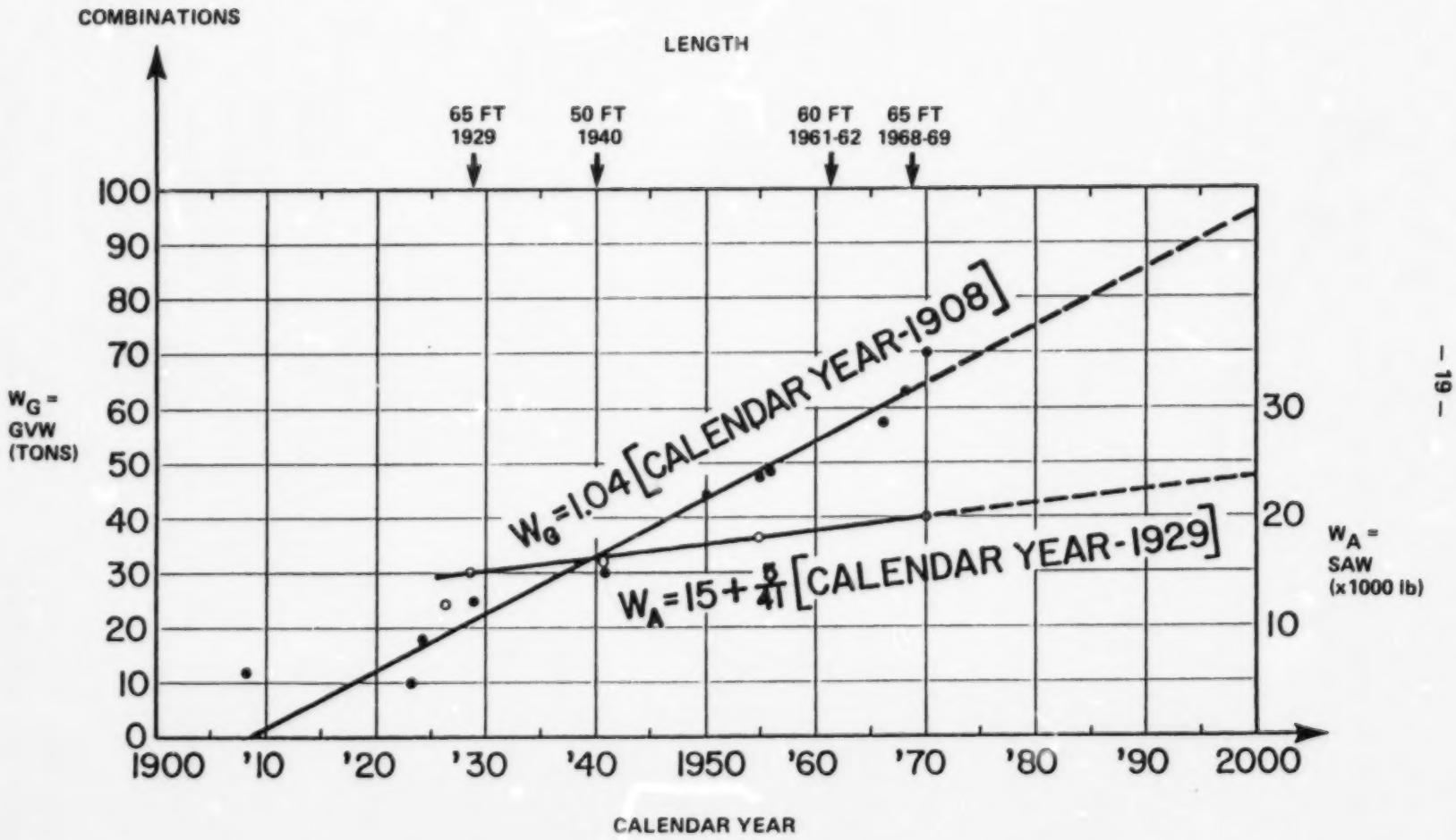

Figure 8/ Trends in Legal Single-Axle Weights (SAWs) and Gross Vehicle Weights (GVWs) in Ontario, 1908-1970

Put another way, the present worth of Ontario's highway system has been estimated at $20 billion. The cost of the enforcement to protect this investment is therefore a very small price to pay.

4/ User-Pay Concepts

Pavement damage caused by heavy and overloaded trucks using the highways is not readily discernible but, rather, manifests itself over a period of time. Bridge damage is usually more obvious and with more immediate consequences. Funds spent on the development of the highway system to benefit the general population are recovered in some form of taxation. However, many studies have shown that heavy trucks generally contribute less than their share, while light trucks and cars are overtaxed. More of the cost of repairing load-related pavement and bridge damage ought to be recoverable from the heavy vehicle road user. As well, enforcement of weight laws will not be effective unless the penalties are higher than "licences" to break the law.

A recent AASHTO study indicates that one 80 000 lb (36 t) truck causes the same damage as 9600 cars. Even though this ratio may be open to question, the taxes paid by heavy trucks in comparison to those paid by cars in the form of licences and fuel tax are nowhere near this proportion.

In the U.S.A., there is considerable interest in introducing third-tier taxes (i.e., taxation in addition to licences and fuel tax), which would be payable by heavy trucks. Several alternatives could be considered.

4.1/ Tonne-Kilometre Taxes

This is probably the fairest taxation concept as it most closely relates to the actual loading and damage caused to the highway system. However, in its purest form, it requires detailed and accurate distance and loading records for each trip, and such information is tedious to gather and can, in any case, only come from the operator and is, therefore, open to abuse. Although such a system is considered administratively burdensome, it is in place in two states in the U.S.A. Since it is based on the total weight carried rather than axle weight, it only relates approximately to pavement damage. One state has an axle-mile tax which attempts to overcome this problem.

4.2/ Weight-Distance Tax

This system is based on the gross-vehicle registered weight and the total distance and is therefore far easier to administer. Again, due to the further approximation, it is only a very rough estimate of each vehicle's share of highway damage cost. However, it is fairly easy to administer, as vehicle distance records have to be maintained for other purposes anyway. It is probably the fairest tax that is also practical to administer. This form of a tax is applied by several states, and there is consideration to adopting it as a federal tax in the U.S.A.

4.3/ Flat Rate and Fuel Taxes

A flat fee for trucks over a prescribed weight limit would be simple to administer and could be designed to recover the appropriate amount of tax from each group of heavy vehicles. However, since it would not be related to distance, it would penalize trucks travelling lower annual distances than the average.

Additional fuel taxes have been proposed as a simple method of allocating the cost based on use. However, larger trucks only use a little more fuel than light and medium trucks. This type of tax, therefore, would tend to shift more of the tax burden onto the lighter trucks. This would be a retrogressive step as heavier trucks do more damage than the lighter trucks, which are already paying more than their share.

At the present time, a combination of a flat fee and increased fuel tax is about to be imposed as a heavy vehicle use tax in the U.S.A. at the federal level. This compromise system still has the limitations of its two parts, as discussed before, but is an attempt to be as fair as possible. It may ultimately be replaced by a weight-distance tax once this concept has been studied in more detail.

In considering the overall economics of providing a highway transportation system, there is no doubt that some form of user-pay taxation system should be introduced to offset the costs due to heavy vehicle transportation.

5/ CONCLUSIONS

- Vehicle weight regulation is an essential part of any highway management system. Weight regulations need to be clearly stated so that understanding them is not a burden on the vehicle operators.

- There is little use in formulating regulations if they are not enforced, so enforcement is an integral part of regulation. Enforcement requires a commitment of resources for appropriate scales and staff, as well as meaningful penalties.

- There are cost benefits to truck operators in operating larger trucks; however, above 40 to 60 t, the benefits are quite marginal.

- As higher axle loads are allowed, road construction and maintenance costs increase very significantly. If they are allowed to increase without check, significant damage will occur to both structures and pavements.

- Ontario's weight laws, based on axle weight, axle spacing, and gross weight, allow maximum loads of 63.5 t. Yet axle and axle spacing criteria ensure that pavement damage is kept within acceptable limits and that structures are not overloaded. Increases in weight allowance above these levels would be of little or no economic benefit to the trucking industry, but would result in an escalation in public expenditures to maintain the integrity of the road system.

- Since heavy trucks do the greatest amount of damage to the highway system, it is reasonable to consider some form of user-payer taxation, such as the weight-distance concept.

NOTES

Ontario

Ministry of
Transportation and
Communications
Hon. Ed Fulton
Minister